Dive into GPGPU programming

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github.com/ashvardanian/SandboxGPUs

Who am I?

Ashot Vardanian, 24 yo, SPb
First OpenGL line at the age of 15

Worked on:

- Web
- Mobile
- Desktop
- Scientific Computing

Working on:

- High Performance Computing
- Artificial Intelligence Research

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Who is this talk for?

You are familiar with C/C++.

You know what a GPU is.

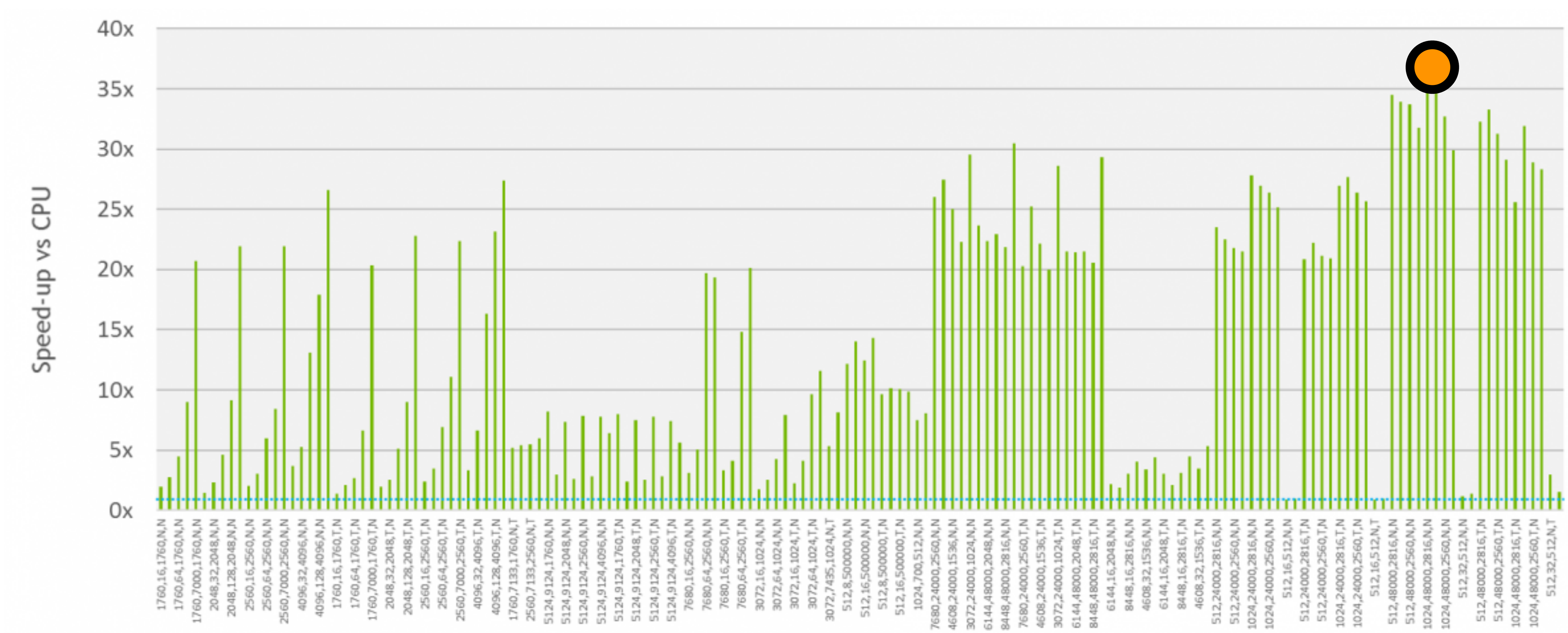
You want to do number-crunching:

- AI & Datascience,
- Video Processing,
- Physics & Bio Simulations.

Not about benchmarking,
but about architecture!

Why GPUs?

...I have heard we can get a 35x performance increase...



What we want?

Write code once, but deploy everywhere!

Optimise performance, but avoid boilerplate!

What we want?

.cpp

Write code once,

but deploy everywhere!

Intel, Nvidia GPUs, AMD, Xilinx FPGA

Optimise performance,

but avoid boilerplate!

What we want?

Unified Language

Write code once,

Modular Compilers

but deploy everywhere!

Tune code without rewriting logic

Optimise performance,

but avoid boilerplate!

Clean APIs

Comparison of recipes

...we will fill this table:

	Simple	Unified	Flexible	Clean
Technology	?	?	?	?
Write code once	?	?	?	?
Deploy everywhere	?	?	?	?
Optimise performance	?	?	?	?
Avoid boilerplate	?	?	?	?

We have a plan!

The Plan

1. **Popular APIs:**
    1. **OpenGL,**
    2. **OpenCL.**
2. Writing Low-level code
3. Existing Libraries & Tools
4. Optimal Recipes

The Plan

1. Popular APIs
2. **Writing Low-level code:**
    1. **OpenCL Language,**
    2. **CUDA Language,**
    3. **GLSL.**
3. Existing Libraries & Tools
4. Optimal Recipes

The Plan

1. Popular APIs
2. Writing Low-level code
3. **Existing Libraries & Tools:**
    1. **Linear Algebra,**
    2. **Lazy Evaluation,**
    3. **Halide,**
    4. **SyCL.**
4. Optimal Recipes

The Plan

1. Popular APIs
2. Writing Low-level code
3. Existing Libraries & Tools
4. **Optimal Recipes.**

Popular APIs

For CPU-GPU communication

API Support

	OpenGL
Release	1992, SGI
Intel	**Yes**
AMD	**Yes**
Nvidia	**Yes**
Apple	Deprecated
Android	**Yes**

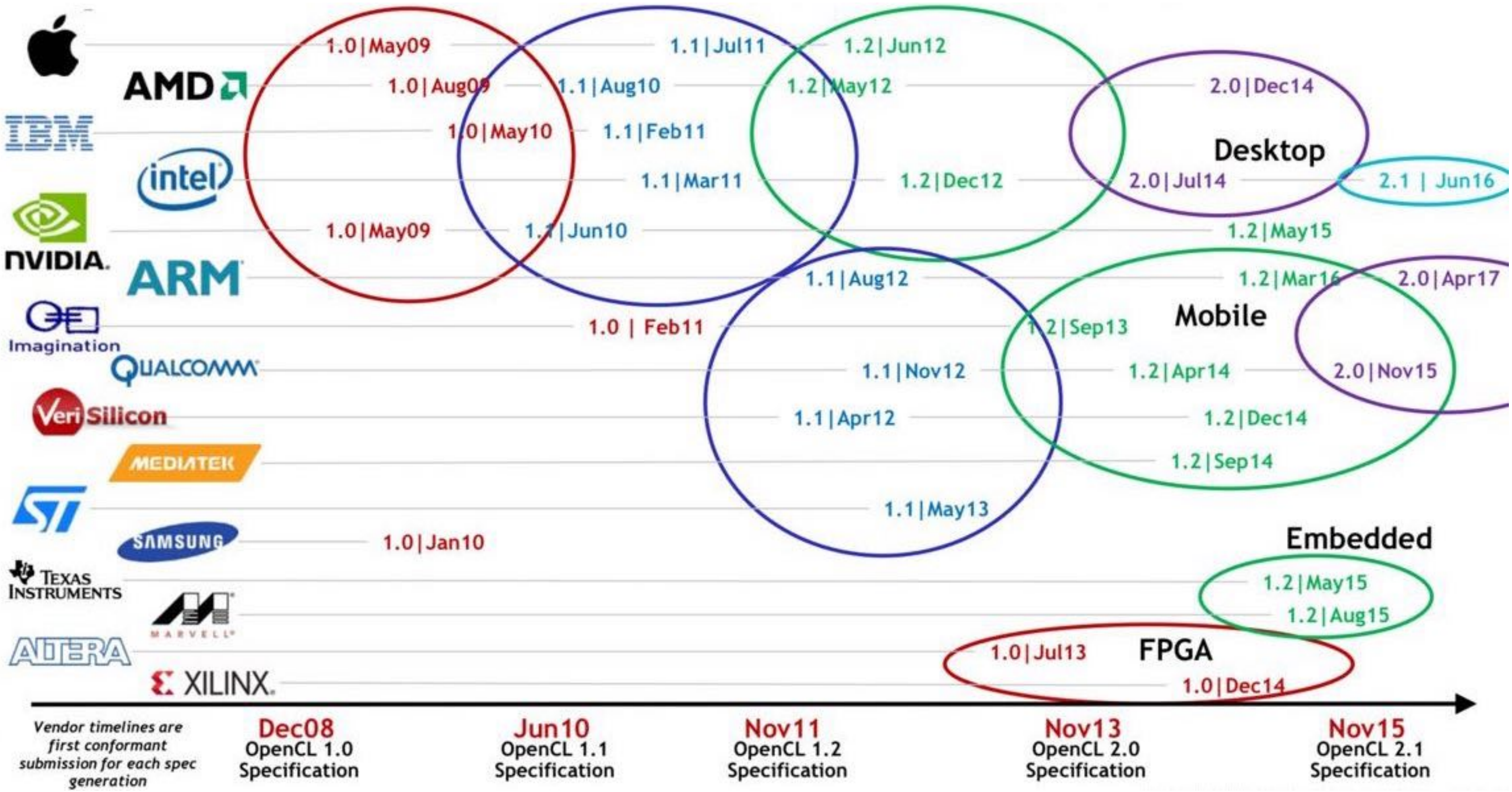
API Support

	OpenGL	CUDA
Release	1992, SGI	2007, Nvidia
Intel	**Yes**	No
AMD	**Yes**	No
Nvidia	**Yes**	**Yes**
Apple	Deprecated	No
Android	**Yes**	No

API Support

	OpenGL	CUDA	OpenCL
Release	1992, SGI	2007, Nvidia	2009, Apple
Intel	**Yes**	No	**Yes**
AMD	**Yes**	No	**Yes**
Nvidia	**Yes**	**Yes**	**Yes**
Apple	Deprecated	No	MacOS
Android	**Yes**	No	Depends

OpenCL support (2015)



API Support

	OpenGL	CUDA	OpenCL	Metal
Release	1992, SGI	2007, Nvidia	2009, Apple	2014, Apple
Intel	**Yes**	No	**Yes**	No
AMD	**Yes**	No	**Yes**	No
Nvidia	**Yes**	**Yes**	**Yes**	No
Apple	Deprecated	No	MacOS	**Yes**
Android	**Yes**	No	Depends	No

API Support

	OpenGL	CUDA	OpenCL	Metal	Vulkan
Release	1992, SGI	2007, Nvidia	2009, Apple	2014, Apple	2016, AMD
Intel	**Yes**	No	**Yes**	No	**Yes**
AMD	**Yes**	No	**Yes**	No	**Yes**
Nvidia	**Yes**	**Yes**	**Yes**	No	**Yes**
Apple	Deprecated	No	MacOS	**Yes**	MoltenVK
Android	**Yes**	No	Depends	No	**Yes**

API Comparison

	OpenGL	CUDA	OpenCL	Metal	Vulkan
Primary Purpose	Graphics	**Compute**	**Compute**	Graphics	Graphics
Base Input Language	C	**C++**	C	**C++**	**Any**
Complexity	Hard ...on Device	**Easy**	**Easy**	Average	Very Hard
Targets Flexibility	Average	Low ...only Nvidia	**Extreme** **...FPGA**	Low ...only Apple	**High**
API Flexibility*	Average	**High****	Average	Average	**High**

API Comparison

		CUDA	OpenCL		Vulkan
Primary Purpose		**Compute**	**Compute**		Graphics
Base Input Language		**C++**	**C**		**Any** SPIR-V
Complexity		**Easy**	**Easy**		**Very Hard**
Targets Flexibility		**Low ...only Nvidia**	**Extreme ...FPGA**		**High**
API Flexibility*		**High****	Average		**High**

Language Syntax

CUDA vs OpenCL. More or less the same.

Parallelism in Language

Which keywords and features must a language have to make parallel programming easy?

Syncronization Primitives

To help threads understand their role

Memory Qualifiers

To limit data visibility

?

Memory Types

CPU

	CUDA	OpenCL
All Threads	Global	Global
Group of Threads	Shared	Local
Single Thread	Local, Register (faster)	Private
Other	Constant, Texture	Constant

OpenGL	Vertex Buffer	Frame Buffer	Texture	Local

Actual Memory Types

...have little to do with physical capabilities of the device! At least from OpenCL perspective!

	i7-7820HQ	Titan V	Radeon Pro 560
Compute Units	8 cores	80 cores	16 cores
Sync-able Group	<1024 threads $\mathbb{N}^1$	<1024 threads $\mathbb{N}^3$	< 256 threads $\mathbb{N}^3$
Constant Buffer	64 Kb	? Kb	64 Kb
Local Memory	32 Kb	? Kb	32 Kb

1 Mb L2

16 Kb L1 per CU

Actual Memory Types

...have little to do with physical capabilities of the device! At least from OpenCL perspective!

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Sync-able Group	<1024 threads $\mathbb{N}^1$	<1024 threads $\mathbb{N}^3$	< 256 threads $\mathbb{N}^3$
Constant Buffer	64 Kb	"In Volta the L1 cache, texture cache, and shared memory are backed by a combined 128 KB data cache."	64 Kb
Local Memory	32 Kb		32 Kb

1 Mb L2

16 Kb L1 per CU

Nvidia GPUs have one real "constant" buffer (64-128 Kb) and allocate rest in global memory.

AMD GPUs often have multiple "constant" buffers (64 Kb each) and allocate rest in global memory.

Memory Qualifiers

	CUDA	OpenCL
All Threads	__device__	__global
Group of Threads	__shared__	__local
Single Thread	~	~
Other	__constant__	__constant

CPU

```
void sum_2_vecs(float const * xA,
                float const * xB,
                float * y,
                int const xLen);
```

GPU version

```
kernel
void sum_2_vecs(global float const * xA,
                global float const * xB,
                global float * y);
```

Terminology

CUDA		OpenCL
Stream Multiprocessor	**Core on CPU**	Compute Unit
Thread	**Thread on CPU**	Work-Item
Block		Work-Group
__global__ function		__kernel function
__device__ function		~

Kernels Indexing

	CUDA	OpenCL
	gridDim	get_num_groups()
	blockDim	get_local_size()
	blockIdx	get_group_id()
	threadIdx	get_local_id()
Ugly	blockIdx * blockDim + threadIdx	get_global_id()
Ugly	gridDim * blockDim	get_global_size()

Kernels Synchronization

	CUDA	OpenCL	
Group	__syncthreads()	barrier(...)	
All	__threadfence()	~	
Group Memory	__threadfence_block()	mem_fence(...)	
	~	read_mem_fence(...)	?
	~	write_mem_fence(...)	?

Parallelism in Language

Which keywords and features must a language have to make parallel programming easy?

Syncronization Primitives

gridDim

get_group_id(0)

__threadfence_block()

Memory Qualifiers

in

__global

__shared__

?

Code Examples

Why would you want to write low-level kernels?

Data-Parallel Tasks

...brute-force scaling of simple
non-concurrent problems

inputs:																
operator:	sin				exp				cos				log			
outputs:																

Data-Parallel Tasks

...brute-force scaling of simple
non-concurrent problems

inputs:																
inputs:																
operator:	+ | - | x | ÷				pow				fmod				atan2			
outputs:																

Vector Sum: C

```c
void sum_2_vectors(float const * xA,
                   float const * xB,
                   float * y,
                   int const xLen) {
    for (int i = 0; i < xLen; i ++)
        y[i] = xA[i] + xB[i];
}
```

Vector Sum: OpenCL

```
kernel void sum_2_vectors(global float const * xA,
                          global float const * xB,
                          global float * y) {
    int i = get_global_id(0);
    y[i] = xA[i] + xB[i];
}
```

Vector Sum: GLSL

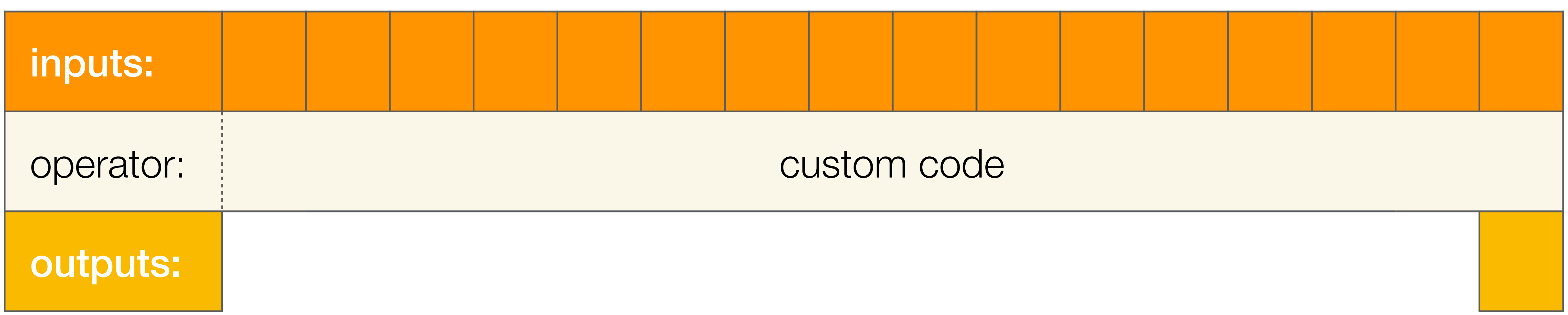
```
#version 450

layout(binding = 0) in buffer lay0 { float xA[]; };
layout(binding = 1) in buffer lay1 { float xB[]; };
layout(binding = 2) out buffer lay2 { float y[]; };

void main() {
    uint const i = gl_GlobalInvocationID.x;
    y[i] = xA[i] + xB[i];
}
```

Concurrent Tasks

...synchronization nightmare
and benchmarks heaven!

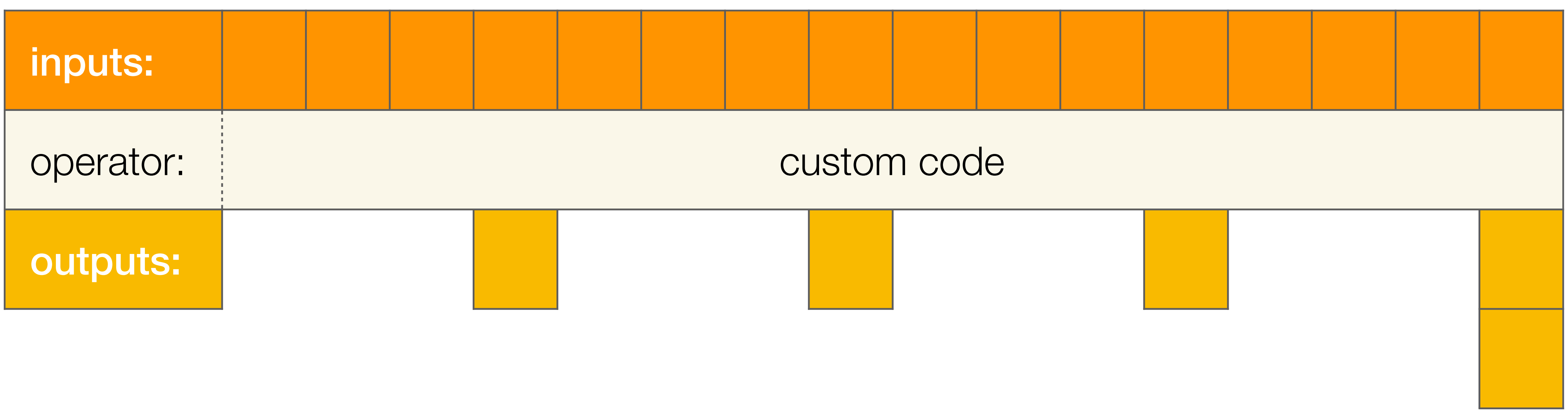


Reduction: C

```
void reduce(float const * x,
            float * y,
            int const xLen) {
    *y = 0;
    for (int i = 0; i < xLen; i ++)
        *y += x[i];
}
```

Concurrent Tasks

...force us to inject memory synchronization barriers and loops, that compiler won't unroll!



Reduction: OpenCL (1)

```
__kernel
void reduce_simple(__global float const * xArr, __global float * yArr,
                   int const xLen, __local float * mBuffer) {
    int const lIdxGlobal = get_global_id(0);
    int const lIdxInBlock = get_local_id(0);
    mBuffer[lIdxInBlock] = (lIdxGlobal < xLen) ? xArr[lIdxGlobal] : 0;

    barrier(CLK_LOCAL_MEM_FENCE);
    int lBlockSize = get_local_size(0);
    int lBlockSizeHalf = lBlockSize / 2;
    while (lBlockSizeHalf > 0) {
        if (lIdxInBlock < lBlockSizeHalf) {
           mBuffer[lIdxInBlock] += mBuffer[lIdxInBlock + lBlockSizeHalf];
           if ((lBlockSizeHalf * 2) < lBlockSize) {
                if (lIdxInBlock == 0)
                    mBuffer[lIdxInBlock] += mBuffer[lIdxInBlock + (lBlockSize - 1)];
            }
        }
        barrier(CLK_LOCAL_MEM_FENCE);
        lBlockSize = lBlockSizeHalf;
        lBlockSizeHalf = lBlockSize / 2;
    }

    if (lIdxInBlock == 0) yArr[get_group_id(0)] = mBuffer[0];
}
```

Reduction: OpenCL (2)

```
__kernel
void reduce_unrolled(__global float const * xArr, __global float * yArr,
                     int const xLen, __local float * mBuffer) {
    int const lIdxInBlock = get_local_id(0);
    int const lIdxGlobal = get_group_id(0) * (get_local_size(0) * 2) + get_local_id(0);
    int const lBlockSize = get_local_size(0);
    mBuffer[lIdxInBlock] = (lIdxGlobal < xLen) ? xArr[lIdxGlobal] : 0;

    if (lIdxGlobal + get_local_size(0) < xLen)
        mBuffer[lIdxInBlock] += xArr[lIdxGlobal + get_local_size(0)];
    barrier(CLK_LOCAL_MEM_FENCE);

#pragma unroll 1
    for (int lTemp = get_local_size(0) / 2; lTemp > 32; lTemp >>= 1)  {
        if (lIdxInBlock < lTemp)
            mBuffer[lIdxInBlock] += mBuffer[lIdxInBlock + lTemp];
        barrier(CLK_LOCAL_MEM_FENCE);
    }

    if (lIdxInBlock < 32) {
        if (lBlockSize >=  64) { mBuffer[lIdxInBlock] += mBuffer[lIdxInBlock + 32]; }
        if (lBlockSize >=  32) { mBuffer[lIdxInBlock] += mBuffer[lIdxInBlock + 16]; }
        if (lBlockSize >=  16) { mBuffer[lIdxInBlock] += mBuffer[lIdxInBlock +  8]; }
        if (lBlockSize >=   8) { mBuffer[lIdxInBlock] += mBuffer[lIdxInBlock +  4]; }
        if (lBlockSize >=   4) { mBuffer[lIdxInBlock] += mBuffer[lIdxInBlock +  2]; }
        if (lBlockSize >=   2) { mBuffer[lIdxInBlock] += mBuffer[lIdxInBlock +  1]; }
    }

   if (lIdxInBlock == 0) yArr[get_group_id(0)] = mBuffer[0];
}
```

Existing Libs & Tools

The complexity of Choice

Linear Algebra

	Intel MKL	cuBLAS	CLBlast
Types	Basic	**Basic, FP16, INT8**	Basic, FP16
Performance	+	**+++**	++
APIs	BLAS, LAPACK...	BLAS +	BLAS

BLAS Levels	Vector-Vector	Matrix-Vector	Matrix-Matrix

LAPACK	Least Squares	Eigenvalues	Factorization

Optimized kernels are chained into slow pipelines!

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Vectors Sum?

Array Sum Reduction?

152 Ops!

Optimized kernels are chained into slow pipelines!

Linear Algebra

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BLAS Levels	Vector-Vector	Matrix-Vector	Matrix-Matrix
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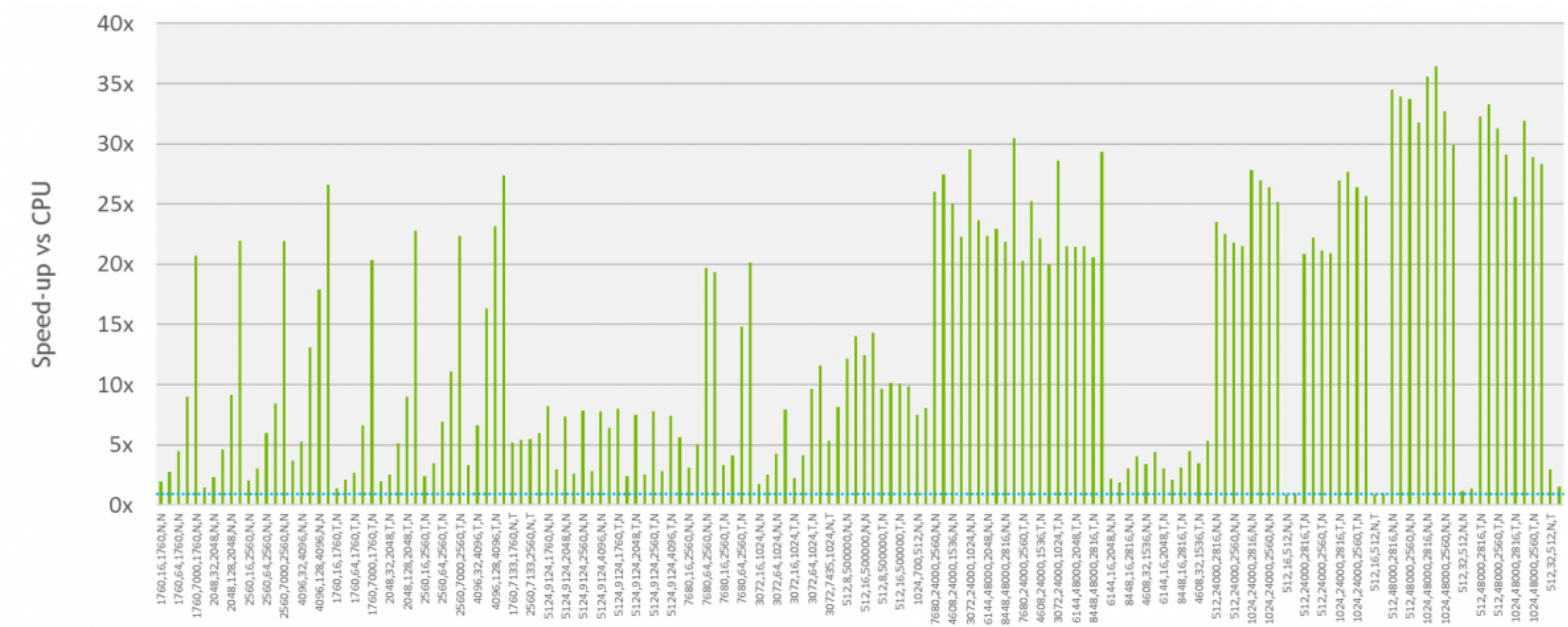
Vectors Sum?
SAXPY with a=1

Array Sum Reduction?
SDOT with unit vector

152 Ops!

<u>Optimized kernels are chained into slow pipelines!</u>



	E5-2690v4	Gold 6262V	V100
Float Performance	+	++	**+++**
Cores	14	24	14
Year	2016	2019	2017
Price	2,000-2,500 USD	**3,000 USD**	8,000 USD

Lazy Evaluation Graph

Lazy	Eigen	ArrayFire	Boost. Compute	Thrust	VexCL
Stars	10k	2.8k	1K	2.5k	565
Type-Safe	**Yes**	No	Yes	Yes	Yes
Backends	OpenMP, CUDA?	**OpenCL, CUDA, etc.**	OpenCL	CUDA, OpenMP	OpenCL, CUDA, OpenMP

<u>Very different functionality and inconsistent APIs.</u>
<u>Potential Licensing issues.</u>

Data-Parallel Tasks

...again, but now with higher level heterogeneous computing tools!

inputs:																
operator:	sin				exp				cos				log			
outputs:																

Cost of Memory Access

...is much higher, than cost of compute, so we need **kernel fusion!**

	Power	
ALU	1 pJ	
Load from SRAM	3 pJ	
Move 10 mm on-chip	30 pJ	
Send off-chip	500 pJ	
Send to DRAM	1 nJ	**1,000x more**
Send over LTE	10 μJ	**10,000,000x more**

Parallelism in Language

...we want to separate the inner part of the "for" loop and the enumeration order

Syncronization Primitives	Memory Qualifiers	Order Descriptors
To help threads understand their role	To limit data visibility	To simplify loops optimization

How Halide works?

...by separating the inner loop logic!

```
func(i) = lA(i) + lB(i);
```

How Halide works?

...and by making loops implicit!

```
void sum_2_vectors(float const * xA,
                   float const * xB,
                   float * y,
                   int const xLen) {
    Halide::Buffer<bFlt32> lA { const_cast<float *>(xA), xLen, "xA" };
    Halide::Buffer<bFlt32> lB { const_cast<float *>(xB), xLen, "xB" };
    Halide::Var i { "i" };
    Halide::Func func;

    func(i) = lA(i) + lB(i);

    Halide::Buffer<bFlt32> lOut = func.realize(xLen);
    std::copy_n(lOut.data(), xLen, y);
}
```

Function body

The "for" loop

How Halide works?

```
void sum_2_vectors(float const * xA,
                   float const * xB,
                   float * y,
                   int const xLen) {
    Halide::Buffer<bFlt32> lA { const_cast<float *>(xA), xLen, "xA" };
    Halide::Buffer<bFlt32> lB { const_cast<float *>(xB), xLen, "xB" };
    Halide::Var i { "i" };
    Halide::Func func;

    func(i) = lA(i) + lB(i);

    Halide::Buffer<bFlt32> lOut = func.parallel(i).realize(xLen);
    std::copy_n(lOut.data(), xLen, y);
}
```

Parallel "for" loop

How Halide works?

```
void sum_2_vectors(float const * xA,
                   float const * xB,
                   float * y,
                   int const xLen) {
    Halide::Buffer<bFlt32> lA { const_cast<float *>(xA), xLen, "xA" };
    Halide::Buffer<bFlt32> lB { const_cast<float *>(xB), xLen, "xB" };
    Halide::Var i { "i" };
    Halide::Func func;

    func(i) = lA(i) + lB(i);

    Halide::Buffer<bFlt32> lOut = func.vectorize(i, 8).realize(xLen);
    std::copy_n(lOut.data(), xLen, y);
}
```

Vectorized "for" loop with "float8"

How Halide works?

```
void sum_2_vectors(float const * xA,
                   float const * xB,
                   float * y,
                   int const xLen) {
    Halide::Buffer<bFlt32> lA { const_cast<float *>(xA), xLen, "xA" };
    Halide::Buffer<bFlt32> lB { const_cast<float *>(xB), xLen, "xB" };
    Halide::Var i { "i" }, j { "j" }, k { "k" };
    Halide::Func func;

    func(i) = lA(i) + lB(i);

    func.vectorize(i, j, k, 8);
    Halide::Buffer<bFlt32> lOut = func.parallel(j).unroll(k).realize(xLen);
    std::copy_n(lOut.data(), xLen, y);
}
```

Transforming a 1 dimensional "for"-loop into 2D loop

Unroll the inner loop!

Blur Filter: C++

...the baseline for comparison!

```
void box_filter_3x3(const Image &in, Image &blury) {
  Image blurx(in.width(), in.height());  // allocate blurx array

  for (int y = 0; y < in.height(); y++)
    for (int x = 0; x < in.width(); x++)
      blurx(x, y) = (in(x-1, y) + in(x, y) + in(x+1, y))/3;

  for (int y = 0; y < in.height(); y++)
    for (int x = 0; x < in.width(); x++)
      blury(x, y) = (blurx(x, y-1) + blurx(x, y) + blurx(x, y+1))/3;
}
```

Slow

Fast

Blur Filter: Halide

Halide

0.9 ms/megapixel

```
Func box_filter_3x3(Func in) {
  Func blurx, blury;
  Var x, y, xi, yi;

  // The algorithm - no storage, order
  blurx(x, y) = (in(x-1, y) + in(x, y) + in(x+1, y))/3;
  blury(x, y) = (blurx(x, y-1) + blurx(x, y) + blurx(x, y+1))/3;

  // The schedule - defines order, locality; implies storage
  blury.tile(x, y, xi, yi, 256, 32)
       .vectorize(xi, 8).parallel(y);
  blurx.compute_at(blury, x).store_at(blury, x).vectorize(x, 8);

  return blury;
}
```

Sugar: tiling!

C++

With platform-specific SIMD!

0.9 ms/megapixel

```
void box_filter_3x3(const Image &in, Image &blury) {
  __m128i one_third = _mm_set1_epi16(21846);
  #pragma omp parallel for
  for (int yTile = 0; yTile < in.height(); yTile += 32) {
    __m128i a, b, c, sum, avg;
    __m128i blurx[(256/8)*(32+2)]; // allocate tile blurx array
    for (int xTile = 0; xTile < in.width(); xTile += 256) {
      __m128i *blurxPtr = blurx;
      for (int y = -1; y < 32+1; y++) {
        const uint16_t *inPtr = &(in[yTile+y][xTile]);
        for (int x = 0; x < 256; x += 8) {
         a = _mm_loadu_si128((__m128i*)(inPtr-1));
         b = _mm_loadu_si128((__m128i*)(inPtr+1));
         c = _mm_load_si128((__m128i*)(inPtr));
         sum = _mm_add_epi16(_mm_add_epi16(a, b), c);
         avg = _mm_mulhi_epi16(sum, one_third);
         _mm_store_si128(blurxPtr++, avg);
         inPtr += 8;
      }}
      blurxPtr = blurx;
      for (int y = 0; y < 32; y++) {
        __m128i *outPtr = (__m128i *)(&(blury[yTile+y][xTile]));
        for (int x = 0; x < 256; x += 8) {
          a = _mm_load_si128(blurxPtr+(2*256)/8);
          b = _mm_load_si128(blurxPtr+256/8);
          c = _mm_load_si128(blurxPtr++);
          sum = _mm_add_epi16(_mm_add_epi16(a, b), c);
          avg = _mm_mulhi_epi16(sum, one_third);
          _mm_store_si128(outPtr++, avg);
}}}}}
```

Laplacian Filter

...real life example!

	Reference C++
LOC	300
Time	?
Performance	1x

Laplacian Filter

...real life example!

	Reference C++	Adobe CPU
LOC	300	1,500
Time	?	3 months
Performance	1x	10x

Laplacian Filter

...real life example!

	Reference C++	Adobe CPU	Halide CPU
LOC	300	1,500	**60**
Time	?	3 months	**1 day**
Performance	1x	10x	**20x**

Laplacian Filter

...real life example!

	Reference C++	Adobe CPU	Halide CPU	Halide GPU
LOC	300	1,500	**60**	
Time	?	3 months	**1 day**	
Performance	1x	10x	**20x**	**70x**

Vector Sum: SyCL Today

```
void sum_2_vectors(float const * xA,
                   float const * xB,
                   float * y,
                   int const xLen) {

    cl::sycl::queue q;
    cl::sycl::buffer<float, 1> lA { xA, xLen };
    cl::sycl::buffer<float, 1> lB { xB, xLen };
    cl::sycl::buffer<float, 1> lOut { y, xLen };

    q.submit([&](cl::sycl::handler & h) {
        auto hA = lA.get_access<cl::sycl::access::mode::read>(h);
        auto hB = lB.get_access<cl::sycl::access::mode::read>(h);
        auto hOut = lOut.get_access<cl::sycl::access::mode::write>(h);
        h.parallel_for<class kernel_name>(xLen, [=] (cl::sycl::id<1> i) {
            hOut[i] = hA[i] + hB[i];
        });
    });
    q.wait();
}
```

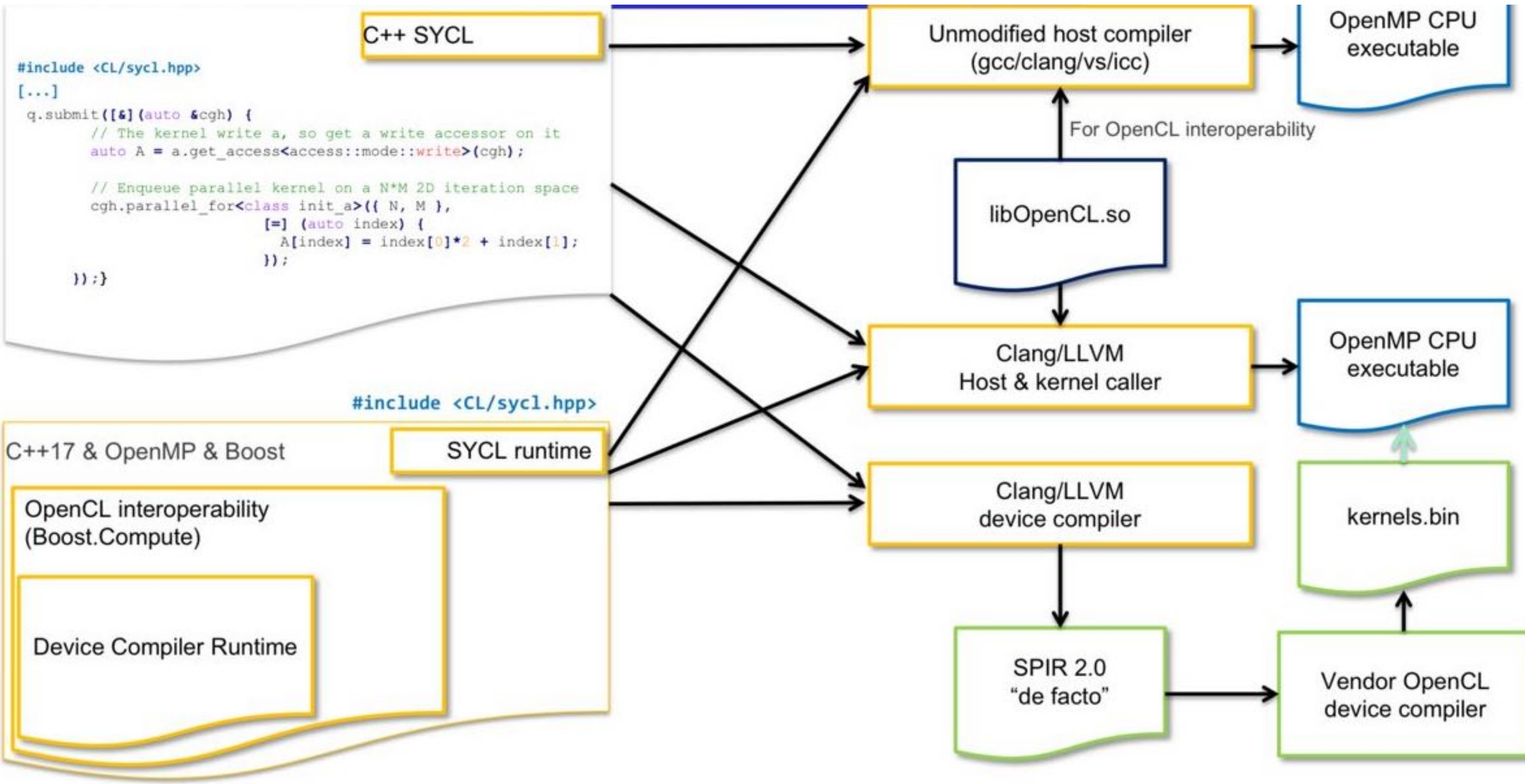
A lonely meaningful line, surrounded by boilerplate!

Vector Sum: SyCL STL

```
void sum_2_vectors(float const * xA,
                   float const * xB,
                   float * y,
                   int const xLen) {

    std::transform(cl::sycl::uniform_policy,
                   std::span(xA, xLen), std::span(xB, xLen),
                   std::span(y, xLen),
                   std::plus<float> { });
}
```

How SyCL works?



How SyCL works?

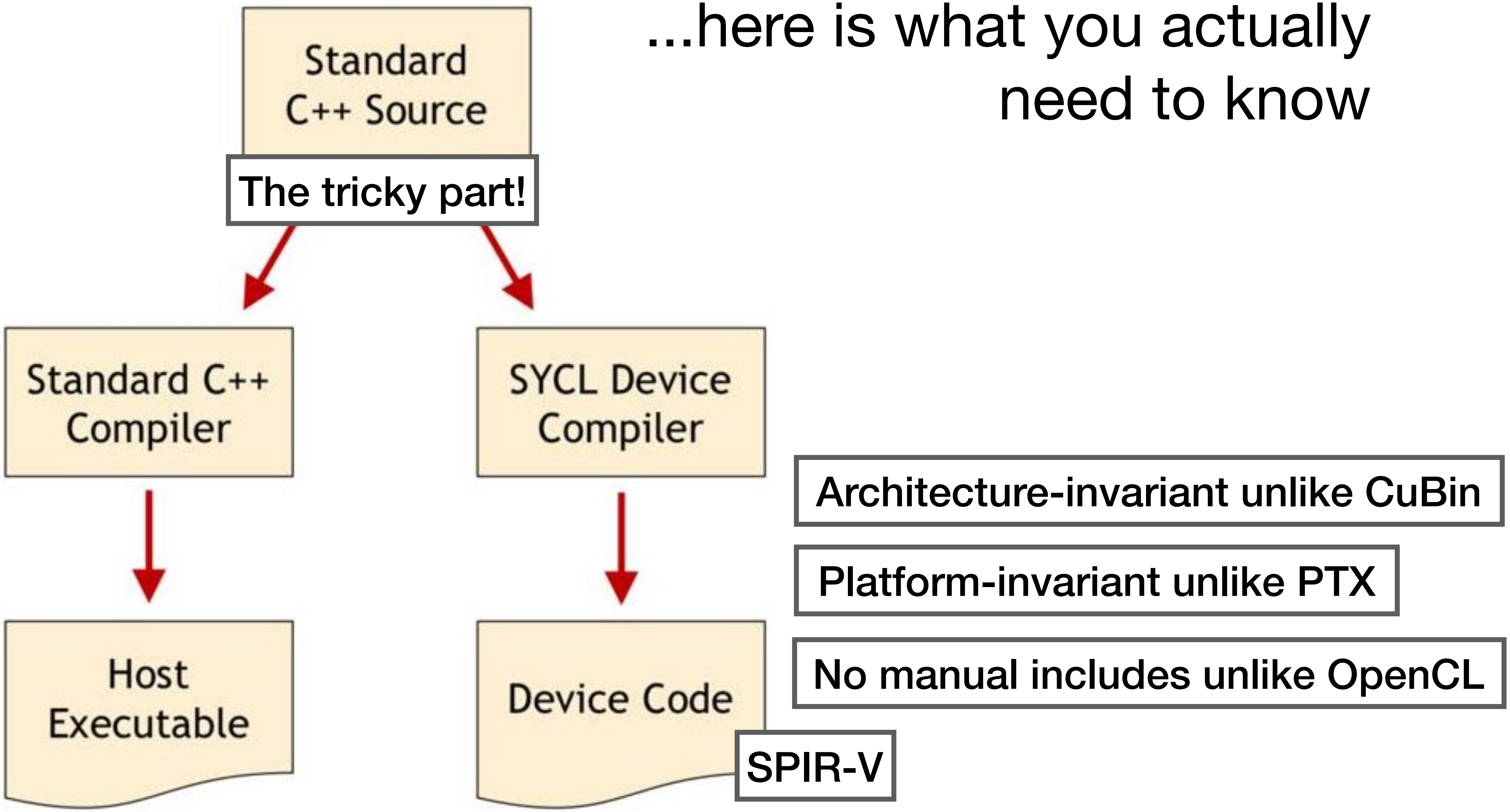
...here is what you actually
need to know

It's not a language!
It's not a library!
It's not a compiler!
It's a combination of:

- library,
- compiler extensions!

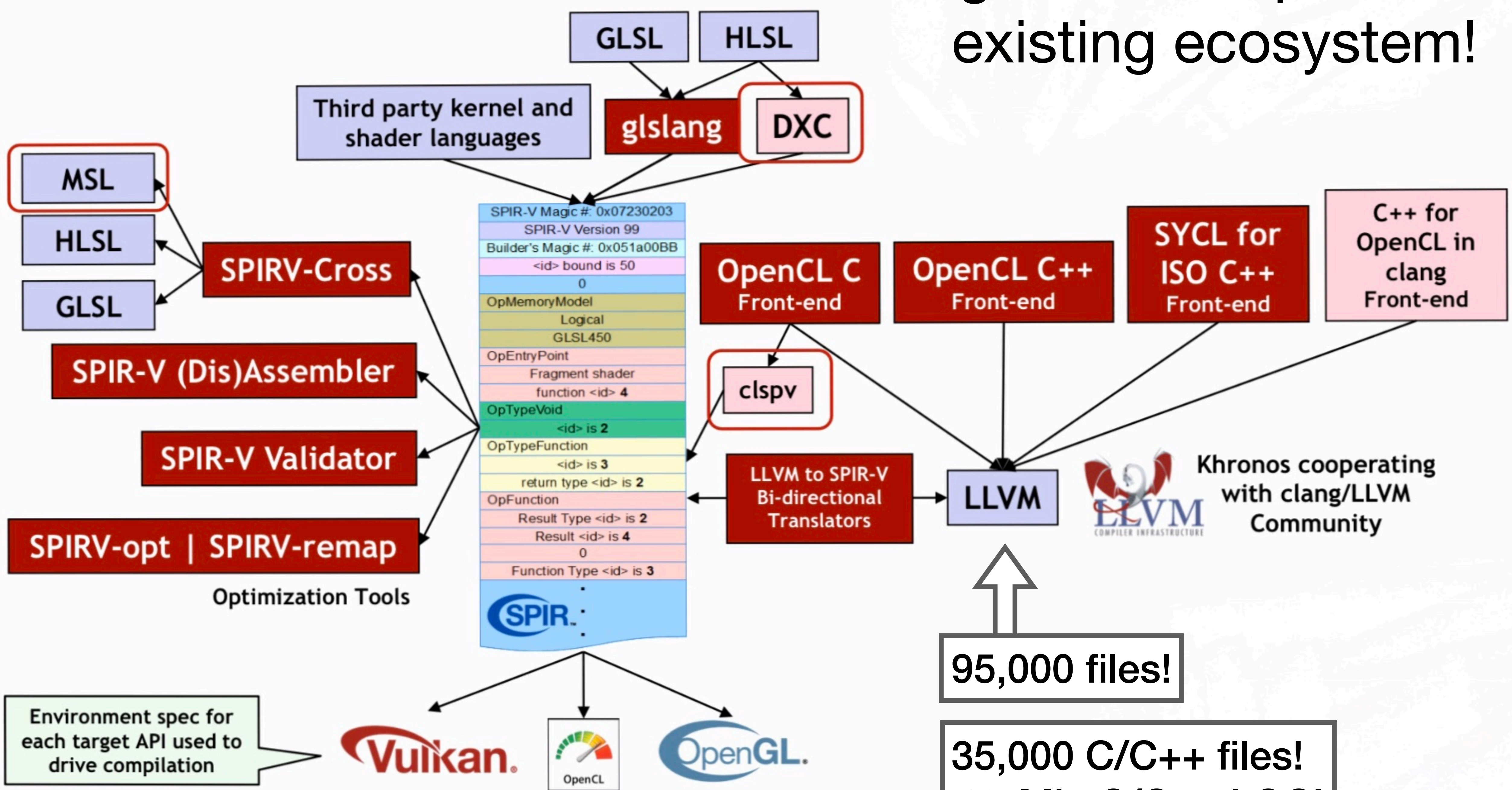
How SyCL works?

...here is what you actually need to know



How SyCL works?

...it grows on top of the existing ecosystem!

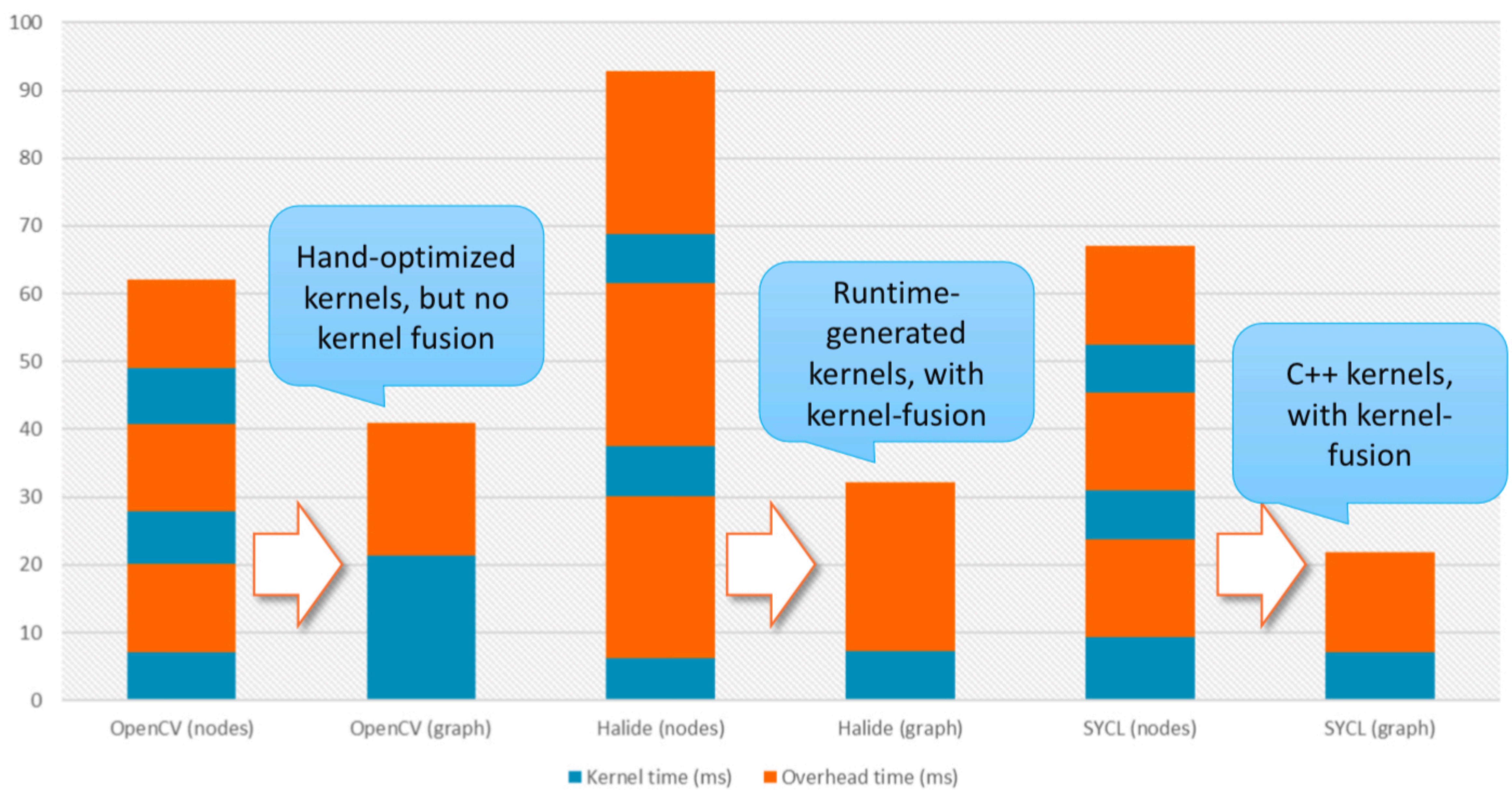


95,000 files!

35,000 C/C++ files!
5,5 Mln C/C++ LOC!

Kernel Fusion

...impact on <u>pipeline</u> performance!

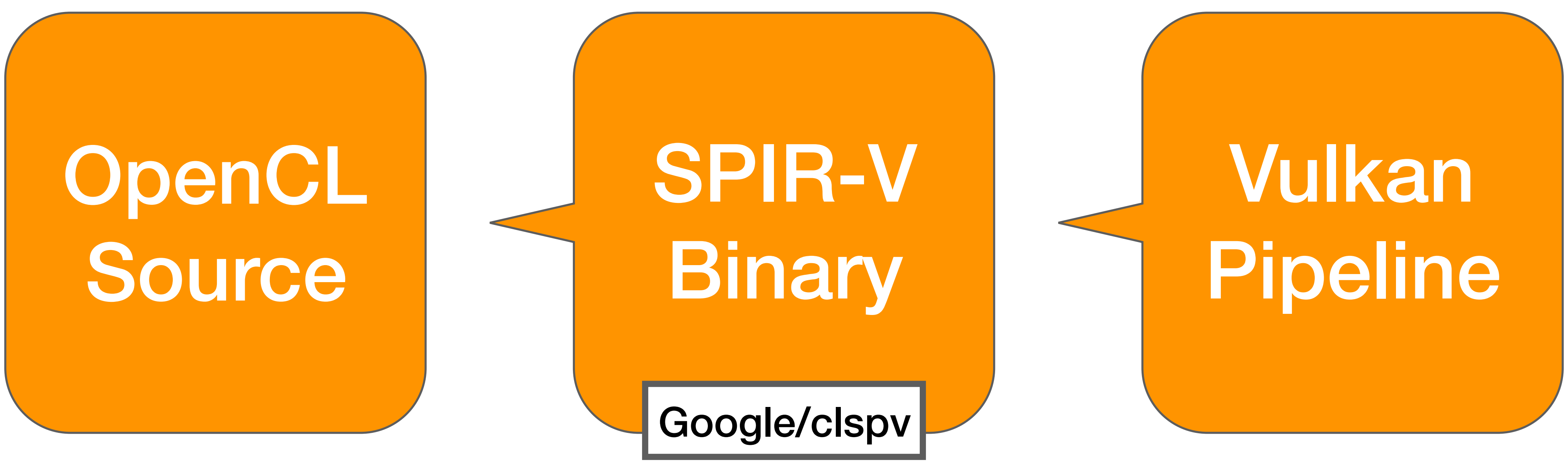


What to choose?

Compromises

Unified solution

...if you want cross platform binaries for your custom hand-made kernels!



OpenCL Source → SPIR-V Binary → Vulkan Pipeline

Pros
Same binary runs everywhere, easy to debug
Concurrent queues
Logical devices can represent SLI groups
Same ecosystem for both graphics and compute

Cons
Separate CL/C++ codebases
Experimental stage compilers
No support for CUDA features: warp shuffles, hardware-specific instructions *, L1 cache tuning
No modern C++ support until version 2.2

No work-arounds?

100 TFlops?!

Flexible solution

...if you want a flexible tool
here and now!

Embedded DSL in C++

Halide Compiler

Custom Schedulers

CUDA

OpenCL

OpenGL

Maybe Vulkan again?

Haxagon DSP

Metal

Direct 3D

Embedded DSL in C++

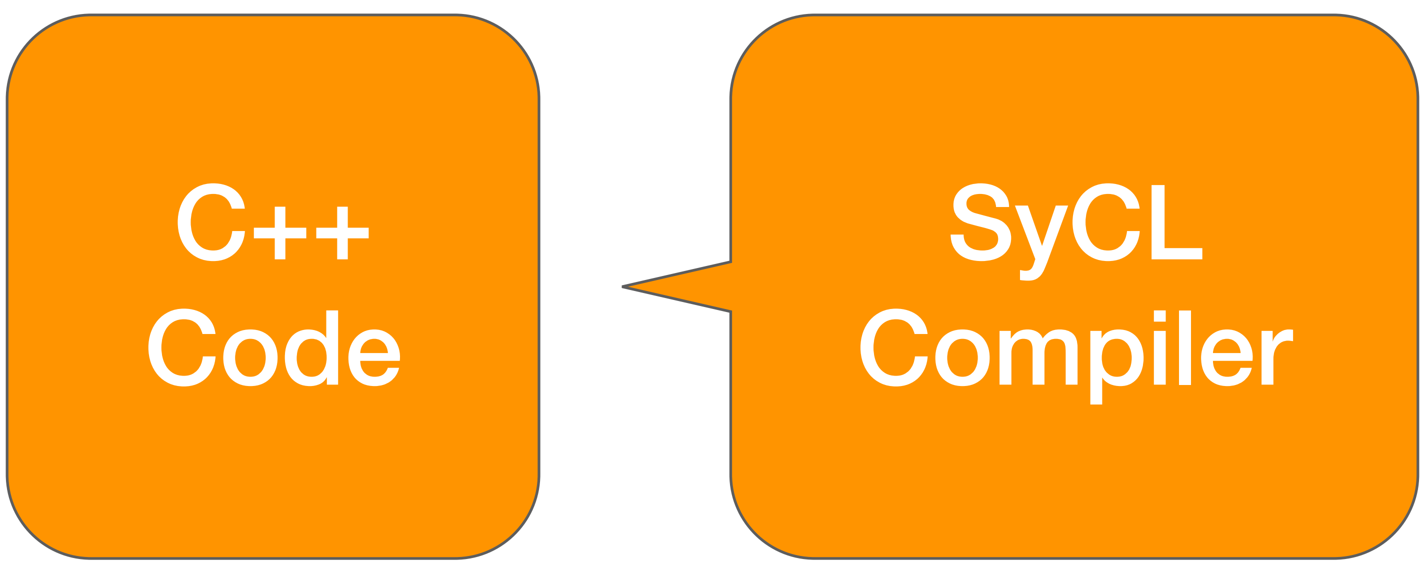
Halide Compiler

Custom Scheduler

Pros	Cons
Great for prototyping and benchmarking	**Turing-incomplete**
Generate binaries for every platform	**Limited number of supported types**
Easy to export computational graphs into other libs	Huge LLVM dependency
Easy to debug algorithms	Non-standard C++
Built-in tools for image procssing	Bad error messages

Clean solution

...if you want some classical
type-safe C++!



C++
Code

SyCL
Compiler

Pros
Use C++ templates and lambda functions for host & device code - just pass "sycl" policy
SYCL will not create C++ language extensions, but instead add features via C++ library
Does kernel fusion
Layered over OpenCL

Cons
Very immature, stability and C++17 adoption is expected closer to 2020
Underlying implementation requires compiler support
Kernel fusion may be weak
Boost.Compute dependency

Simple solution

...if you want a brute-force accelerator for simple data-parallel number-crunching!

High level GPGPU library of choice like ArrayFire

High level GPGPU library of choice like ArrayFire

Pros
Already packed with binaries for multiple backends
Minimal coding required

Cons
Weak kernel fusion

Comparison of recipes

...lets summarize our results!

	Simple	Unified	Flexible	Clean
Technology	**ArrayFire**	**CL & SPIR-V**	**Halide**	**C++ SyCL**
Write code once	Yes	Separate Files	T-Incomplete	Yes
Deploy everywhere	Almost	Yes	Yes	Eventually
Optimise performance	Average	High	Highest	High
Avoid boilerplate	YES!	Depends	Depends	Yes

Comparison of recipes

...lets summarize our results!

	Max Performance Today			
Technology		CL & SPIR-V	Halide	
Write code once		Yes	T-Incomplete	
Deploy everywhere		Yes	Yes	
Optimise performance		High	Highest	
Avoid boilerplate		Depends	Depends	

Comparison of recipes

...lets summarize our results!

	Sometime in the Future			
Technology				C++ SyCL
Write code once				Yes
Deploy everywhere				Eventually
Optimise performance				High
Avoid boilerplate				Yes

Tips & Tricks

OpenCL Tips

1. Unroll loops & inline functions manually!
2. Violate the IEEE 754 standard:
    - Accuracy: `-cl-unsafe-math-optimizations, -cl-mad-enable`
    - Zeroes: `-cl-finite-math-only, -cl-no-signed-zeros`
3. **Use special functions:**
    - Work with fractions: `remainder(), remqo(), fract()`
    - Perform multiple actions: `fma(), sincos(), expm1(), mad()`
    - OpenCL knows Pi: `tanpi(), sinpi(), atanpi(), atan2pi()`
4. Don't create too many command buffers!

CUDA Tips

1. Similarly, use fast math functions:
    - Half precision: `__hadd()`, `__hadd_sat()`, `__hmul()`, `__hneg()`
    - Control rounding: `__fadd_rd()`, `__fadd_rz()`, `__fadd_rn()`
    - Perform multiple actions: `__fmaf_rd()`, `__sincosf()`
2. **Use the ecosystem!**
    - **Mixed Precision Math libraries**.
    - cuBLAS & cuDNN.
3. Transform CUDA stream code into multi-GPU reusable dependency graph.

Existing Ecosystem

Symbolic Graph	**TF, PyTorch**, **cuDNN**, MKL-DNN
Lazy Evaluation	Eigen, **TF**, VexCL, ArrayFire
Linear Algebra	Eigen, MKL, VexCL, **cuBLAS**, **ArrayFire**, Boost.Compute
Scheduling	Intel TBB, Vulkan, **OpenMP**, SyCL
Language & Extensions*	**CUDA**, **OpenCL**, GLSL, OpenMP, OpenACC
Compilers*	**LLVM**, **TVM**, GCC

Where to apply?

Unum

Scalable & cheap analytics with modern ML techniques.

Built on top of:

- C++14 since 2015,
- C++17 since 2017,
- OpenCL, LLVM,
- Eigen, ArrayFire.

Working on a new programming language now - **C***.

Why? Existing Problems

Symbolic Graph	**TF, PyTorch**, $\boxed{\text{Too big to navigate \& embed!}}$
Lazy Evaluation	Eigen, **TF**, VexCL, $\boxed{\text{Limited serialisation beyond ONNX!}}$
Linear Algebra	Eigen, MKL, VexCL, **cuBLAS**, **ArrayFire**, Boost.Compute
Scheduling	Intel TBB, Vulkan, **OpenMP**, SyCL $\boxed{\text{Verbose!}}$
Language & Extensions*	**CUDA**, **OpenCL**, $\boxed{\text{Same, but fragmented!}}$
Compilers*	**LLVM**, $\boxed{\text{Single point of failure!}}$

Goals for C*

Performance higher than in C++.

Kernel fusion > Inlining

As simple as Common LISP.

Interpretable into C, OpenCL, CUDA

Flexible like Halide.

Tuning is separate from logic

Q & A

The talk:

- github.com/ashvardanian/SandboxGPUs

The project:

- unum.xyz
- github.com/unumxyz

Me:

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- vk.com/ ashvardanian